

Beaming Effect in Fermi Blazars

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Abstract

The γ -ray loud blazars (flat spectrum radio quasars–FSRQs and BL Lacertae objects–BLs) are very bright in the γ -ray bands, which is perhaps associated with a beaming effect. Therefore, one can expect that the γ -ray luminosity is correlated with the beaming factor. In this paper, we investigated the relation between the radio Doppler factors and the gamma-ray luminosities. Our analysis suggests that the γ -ray luminosity be strongly correlated with the factor of δ_R for the whole sample, FSRQs, and BLs. When the effect of a common redshift is excluded, the correlation still exists for the FSRQs sub-sample suggesting that the γ -rays are strongly beamed. However, the partial correlation analysis does not show a correlation for the small BL Lac sample.

Key words: galaxies:active-galaxies:BL Lacertae objects-galaxies:quasars-galaxies:jets-Fermi(LAT)

1. Introduction

Active galactic nuclei (AGNs) are very interesting, their specially observational properties have attracted many astronomers. Blazars are an even extreme subclass of AGNs. There are two subclasses for blazars: flat spectrum radio quasars(FSRQs) and BL Lacertae objects (BLs), the latter can also be classified further as radio selected BL Lacertae objects (RBLs) and X-ray selected BL Lacertae objects-XBLs from surveys, or high-peaked BL Lacertae objects (HBLs) and low-peaked BL Lacertae objects (LBLs) from spectral energy distribution-SED. Blazars show rapid and large variability, high and variable polarization, superluminal motions in their radio components, and strong γ -ray emissions, etc. (e.g. Abdo et al. 2009, 2010a; Aller et al. 2011; Bastieri 2011; Cellone et al. 2007; Ciprini et al. 2007; Fan et al. 1996, 2011; Fan 2012; Ghisellini et al. 2010; Gupta 2011; Gupta et al. 2004; Marscher et al. 2011; Romero et al. 2002; Wills et al. 1992; Wagner 2010; Urry 2011; Yefimov 2011).

During the EGRET mission, about 60 strong γ -ray emitters were detected with high confidence (Hartman et al. 1999). However, the new generation of γ -ray mission, the Fermi detected a lot of blazars (see Abdo et al 2010a, Ackermann, et al. 2011a). Many interesting results have been come to light although the highly energetic emissions are not very clear (Abdo et al. 2010b; Böttcher et al. 2008; Dermer et al. 2009; Ghisellini et al. 2009; Graff et al. 2008; Hovatta et al. 2009; and Lott 2010). The bright γ -ray emissions and the detected variability suggest that the γ -rays are strongly beamed. Dondi & Ghisellini 1995, Muecke et al. (1997), Fan et al. (1998), Huang, et al. (1999), Cheng et al. (2000), and Pushkarev et al. (2010)

investigated the correlation between the γ -ray and the radio bands. The correlation suggests an indirectly beaming effect in the γ -ray emissions. Arshakian et al. (2010) investigated the correlation between the γ -ray luminosity and the rest-frame radio loudness, $R = S_{VLBA}/S_{opt}$ (where S_{VLBA} is the VLBA flux density at 15 GHz and S_{opt} is the optical flux density at 5100Å) for some γ -ray loud blazars and found a significant positive correlation, which suggests that the strong γ -ray jets have progressively high Doppler factors (or faster speeds) in the radio domain compared to those in the optical regime. Kovalev et al. (2009) found that the median brightness temperature T_b values for Fermi-detected sources are statistically higher than those for the rest of their sample at a 99.9 percent confidence. Savolainen et al. (2010) considered 62 objects with apparent velocity from MOJAVE and Doppler factors from radio variability from Metsahovi Radio Observatory, and compared the sources detected by Fermi and those not-detected. They found that the Fermi-detected blazars have on average higher Doppler factors than the non-Fermi-detected blazars. We found that the γ -ray luminosity is associated with the core-dominance parameter(Fan et al. 2010), the γ -ray variability index is correlated with that in the radio band (Fan et al. 2002), and the γ -ray Doppler factor can be estimated from the radio bands (Zhang, Fan, & Cheng, 2002). All those suggest the beaming effect in the γ -ray emissions.

As proposed by Dermer (1995), the dependence of the γ -ray flux on the Doppler factor can be used to investigate the γ -ray emission mechanism, different emission mechanism has different dependence of the flux density (S_γ) on the γ -ray Doppler factor (δ_γ), namely $S_\gamma \propto \delta^{3+\alpha}$ for a synchrotron self-Compton (SSC) model, and $S_\gamma \propto \delta^{4+2\alpha}$ for an external Compton (EC) model. These indexes ($3+\alpha$ and $4+2\alpha$) are true for transient emission features,

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whereas in a steady jet, the indexes are smaller by one, namely, $2+\alpha$ and $3+2\alpha$. Therefore, one can use that dependence to discuss statistically the γ -ray emission mechanism. Unfortunately, the γ -ray Doppler factors are not available for any γ -ray sample.

If the Doppler factor in the γ -ray region, δ_γ , is the same as that in the radio band, δ_R , then the δ_R can be used to deal with the beaming effect in the γ -ray region and to investigate γ -ray emission mechanisms. Actually, the radio Doppler factors are not easy to estimate although many methods have been proposed (see Lähteenmäki & Valtaoja 1999 for a comparison). Lähteenmäki & Valtaoja (1999) proposed to decompose each flux curve into exponential flares, calculated the variability time scale of the flare and the corresponding brightness temperature, $T_{B,var}$. The variability radio Doppler factor can be estimated using $\delta_{var} = (\frac{T_{B,var}}{T_{B,in}})^{1/3}$, here $T_{B,in} = 5 \times 10^{10} K$ is adopted (see Readhead 1994, Lähteenmäki et al. 1999).

In the present paper, we used the available radio Doppler factor, δ_R , and the γ -ray luminosity calculated from the data given in the paper (Abdo et al. 2010a) to investigate the dependence of the γ -ray luminosity on the radio Doppler factor. This paper is arranged as follows: in the 2nd section, we show the sample and the results; in the 3rd section, we will give some discussions and a brief conclusion. We adopt $H_0 = 73 \text{ km} \cdot \text{s}^{-1} \text{ Mpc}^{-1}$, and the spectral index, α is defined as $f_\nu \propto \nu^{-\alpha}$ through this paper.

2. Sample and Results

From Dermer (1995), for the γ -ray flux density, we have that $S_\gamma \propto \delta^{3+\alpha}$ for an SSC model, and $S_\gamma \propto \delta^{4+2\alpha}$ for an EC model. These indexes ($3+\alpha$ and $4+2\alpha$) are true for transient emission features, whereas in a steady jet, the indexes are smaller by one, namely, $2+\alpha$ and $3+2\alpha$. In the present work, we will only consider the former case. If the γ -ray luminosity is taken into account, then we should expect that

$$L_\gamma \propto \delta^{4+\alpha} \text{ for the SSC model, and}$$

$$L_\gamma \propto \delta^{5+2\alpha} \text{ for the EC model.}$$

In the following sections, we will compile a sample with available radio Doppler factors and the γ -ray detections, and then discuss the dependence of the γ -ray luminosity on the Doppler factors.

2.1. Sample

Based on the catalogue of 1FGL (Abdo et al. 2010a), we compiled the available radio Doppler factors from three literatures, namely, L99: Lähteenmäki & Valtaoja (1999); H09: Hovatta et al. (2009); and F09: Fan et al. (2009). Those radio Doppler factors were determined by the same method, but Doppler factors in Fan et al. (2009) are based on 8 and 15 GHz radio flux monitoring by Uni. of Michigan Radio Observatory whereas those in Lähteenmäki & Valtaoja (1999) and Hovatta et al. (2009)

are based on 22 and 37 GHz observations by Metsahovi Radio Observatory. There are 59 sources, the corresponding data are listed in Table 1. In the Table, column (1) gives the name of the source, column (2) classification, H for HBL, L for LBL, F for FSRQ, column (3) the redshift, column (4) the γ -ray photon flux in 1-100 GeV in units of $\text{photon}/\text{cm}^2/\text{s}$ from Abdo et al. (2010a), column (5) the photon spectrum index from Abdo et al. (2010a), column (6) the γ -ray luminosity in erg/s , column (7) radio Doppler factor, δ_R from L99, column (8) radio Doppler factor, δ_R from H09, and column (9) radio Doppler factor, δ_R from F09.

2.2. Results

For a source, the γ -ray luminosity can be calculated from the detected photons. Here, the integral luminosity is used in our discussion since it is a more robust measure of the gamma-ray output (See Abdo et al. 2010c).

Let

$$\frac{dN}{dE} = N_0 E^{-\alpha_{ph}},$$

here α_{ph} is the photon spectral index, and N_0 can be expressed as

$$N_0 = N_{(E_L \sim E_U)} \left(\frac{1}{E_L} - \frac{1}{E_U} \right), \text{ if } \alpha_{ph} = 2, \text{ otherwise}$$

$$N_0 = \frac{N_{(E_L \sim E_U)} (1 - \alpha_{ph})}{(E_U^{1-\alpha_{ph}} - E_L^{1-\alpha_{ph}})},$$

where $N_{(E_L \sim E_U)}$ is the integral photons in units of $\text{photons} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}$ in the energy range of $E_L - E_U$. Therefore, the flux can be obtained by $f = \int_{E_L}^{E_U} E dN$, which can be expressed as

$$f = N_{(E_L \sim E_U)} \left(\frac{1}{E_L} - \frac{1}{E_U} \right) \ln \frac{E_U}{E_L}, \text{ if } \alpha_{ph} = 2, \text{ otherwise}$$

$$f = N_{(E_L \sim E_U)} \frac{1 - \alpha_{ph}}{2 - \alpha_{ph}} \frac{(E_U^{2-\alpha_{ph}} - E_L^{2-\alpha_{ph}})}{(E_U^{1-\alpha_{ph}} - E_L^{1-\alpha_{ph}})}$$

in units of $\text{GeV} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}$. So, we can get the γ -ray luminosity by

$$L_\gamma = 4\pi d_L^2 (1+z)^{(\alpha_{ph}-2)} f,$$

here d_L is the luminosity distance, and can be expressed in the form

$$d_L = \frac{c}{H_0} \int_1^{1+z} \frac{1}{\sqrt{\Omega_M x^3 + 1 - \Omega_M}} dx$$

from the $\Lambda - \text{CDM}$ model (Pedro & Priyamvada, 2007) with $\Omega_\Lambda \simeq 0.7$, $\Omega_M \simeq 0.3$ and $\Omega_K \simeq 0.0$, and $(1+z)^{(\alpha_{ph}-2)}$ represents a K-correction. The calculated luminosity is listed in Col. 6 in Table 1 for 59 Fermi sources. From the data listed in Table 1, we can get the average values for γ -ray luminosity as follows:

$\langle \log L_\gamma |^{FSRQs} \rangle = 46.85 \pm 1.00 \text{ erg/s}$ for the 36 FSRQs, and

$\langle \log L_\gamma |^{LBLs} \rangle = 45.81 \pm 1.04 \text{ erg/s}$ for the 22 LBLs. For HBL, there is only one source 1219+285, its γ -ray luminosity is $\log L_\gamma = 45.08 \text{ erg/s}$. If it represents the average luminosity of HBLs, then the average values of $\log L_\gamma$

Table 1. A Sample of 59 Fermi Blazars with Radio Doppler Factors

Name (1)	Class (2)	z (3)	F(1-100GeV) (4)	α_γ (5)	log L_γ (6)	δ_R^{L99} (7)	δ_R^{H09} (8)	δ_R^{F09} (9)
PKS 0048-09	L	0.634	4.50E-09	2.2	46.66		9.6	4.97
0133+476	F	0.859	9.59E-09	2.34	47.30	7.09	20.7	6.79
1ES 0212+735	F	2.367	1.03E-09	2.85	47.62	4.16	8.5	9.23
PKS 0215+015	F	1.715	5.97E-09	2.18	47.91			5.61
3C 66A	L	0.444	2.49E-08	1.93	47.13	1.99	2.6	
4C +28.07	F	1.213	3.66E-09	2.52	47.28	7.29	16.1	
PKS 0235+164	L	0.94	3.27E-08	2.14	47.98	16.32	24	20.74
PKS 0336-01	F	0.852	1.18E-09	2.5	46.37	19.01	17.4	5.85
PKS 0420-01	F	0.916	5.65E-09	2.42	47.14	11.72	19.9	7.49
PKS 0422+00	L	0.31	1.04E-09	2.38	45.21	1.7		6.11
PKS 0521-36	F	0.057	2.85E-09	2.6	43.92			1.83
PKS 0528+134	F	2.06	4.01E-09	2.64	47.98	14.22	31.2	19.84
PKS 0605-08	F	0.872	1.87E-09	2.43	46.60	4.53	7.6	4.05
S5 0716+714	L	0.3	1.31E-08	2.15	46.35		10.9	
PKS 0723-008	L	0.128	5.97E-10	2.3	44.11	2.5		
PKS 0735+17	L	0.424	4.42E-09	2.02	46.29	3.17	3.8	
PKS 0736+01	F	0.189	2.31E-09	2.63	44.98	3.08	8.6	
PKS 0754+100	L	0.266	1.98E-09	2.39	45.33	5.52	5.6	7.33
PKS 0808+019	L	1.148	1.07E-09	2.45	46.68			5.39
B3 0814+425	L	0.53	8.73E-09	2.15	46.78	5.84	4.6	
B2 0827+243	F	0.94	1.30E-09	2.79	46.52	15.46	13.1	
PKS 0829+046	L	0.174	2.47E-09	2.5	44.96			3.8
4C +71.07	F	2.172	1.24E-09	2.98	47.63	10.67	16.3	
OJ 287	L	0.306	2.75E-09	2.38	45.62	18.03	17	7.76
B2 0954+25A	F	0.708	7.01E-10	2.41	45.94	4.83	4.3	
S4 0954+55	F	0.896	1.05E-08	2.05	47.46	4.63		
S4 0954+65	L	0.368	5.43E-10	2.51	45.08	6.62	6.2	5.93
PKS 1055+01	F	0.89	7.14E-09	2.29	47.23	7.78	12.2	7.49
PKS 1127-14	F	1.184	2.42E-09	2.73	47.08			3.22
4C +29.45	F	0.724	5.30E-09	2.37	46.85	9.42	28.5	9.63
B2 1215+30	L	0.13	6.66E-09	1.98	45.33			0.94
1219+285	H	0.102	6.92E-09	2.06	45.08	1.56	1.2	
3C 273	F	0.158	9.55E-09	2.75	45.40	5.71	17	6.05
3C 279	F	0.536	3.24E-08	2.32	47.31	16.77	24	4.16
B2 1308+32	F	0.996	6.76E-09	2.3	47.33	11.38	15.4	11.58
PKS 1335-127	F	0.539	2.14E-09	2.5	46.10			6.38
PKS 1406-076	F	1.494	1.77E-09	2.42	47.21	8.26		
PKS 1502+106	F	1.839	6.70E-08	2.22	49.04	11.13	12	
PKS 1510-08	F	0.36	4.86E-08	2.41	47.03	13.18	16.7	7.64
B2 1611+34	F	1.397	5.38E-10	2.29	46.62	5.04	13.7	3.36
B3 1633+382	F	1.814	6.78E-09	2.47	48.03	8.83	21.5	5.29
PKS 1717+177	L	0.137	4.72E-09	2.01	45.20			1.94
PKS 1725+044	F	0.296	1.27E-09	2.65	45.18	2.46	3.8	
PKS 1730-13	F	0.902	3.57E-09	2.34	46.93		10.7	11.84
S5 1749+701	L	0.77	1.99E-09	2.05	46.57			3.75
4C +09.57	L	0.322	6.45E-09	2.29	46.07	15.85	12	
8C 1803+784	L	0.68	3.04E-09	2.35	46.54	6.45	12.2	4.7
3C 371	L	0.051	1.88E-09	2.6	43.64	1.8	1.1	1.05
4C +56.27	L	0.664	2.67E-09	2.34	46.46		6.4	2.5
PKS B1921-293	F	0.353	1.40E-09	2.4	45.46			9.51
8C 2007+777	L	0.342	1.43E-09	2.42	45.44	5.13	7.9	4.68
4C -02.81	F	1.285	8.13E-10	2.31	46.70			7
PKS 2145+06	F	0.99	7.48E-10	2.56	46.34	7.81	15.6	4.35
PKS 2155-152	F	0.672	9.24E-10	2.51	45.98			2.31
BL Lac	L	0.069	7.10E-09	2.38	44.56	3.91	7.3	2.77
3C 446	F	1.404	2.15E-09	2.53	47.23	11.38	16	9.93

suggest a sequence that $\log L_\gamma|^{FSRQs} > \log L_\gamma|^{LBLs} > \log L_\gamma|^{HBLs}$.

For the beaming effect in the γ -ray emissions, we discussed it using the γ -ray luminosity, $\log L_\gamma$ and the radio Doppler factor, δ_R by discussing the linear correlation between $\log L_\gamma - \log \delta^{4+\alpha}$ (or $\log \delta^{5+2\alpha}$). The Pearson's correlation coefficient r is expressed as (see Press 1994, Pavlidou et al. 2012)

$$r = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2} \sqrt{\sum (y_i - \bar{y})^2}}$$

here, \bar{x} is the mean of the x_i 's, \bar{y} is the mean of the y_i 's, and (x_i, y_i) correspond to $(\log \delta_i^{4+\alpha}$ (or $\log \delta^{5+2\alpha}$), $\log L_{\gamma,i}$). Since the radio Doppler factors are from 3 different literatures, we considered the relationship between the γ -ray luminosity, $\log L_\gamma$ and the radio Doppler factor, δ_R for 3 samples separately, the results are:

$\log L_\gamma(\text{erg/s}) = (0.41 \pm 0.09) \log \delta_R^{4+\alpha_\gamma} + (44.67 \pm 0.42)$ with a correlation coefficient $r = 0.597$ and a chance probability of $p < 10^{-4}$, and $\log L_\gamma(\text{erg/s}) = (0.28 \pm 0.06) \log \delta_R^{5+2\alpha_\gamma} + (44.71 \pm 0.42)$ with a correlation coefficient $r = 0.590$ and a chance probability of $p < 10^{-4}$ for the whole sample of 43 sources from Lähtenmäki & Valtaoja (1999). The corresponding plots are shown in Fig 1.

$\log L_\gamma(\text{erg/s}) = (0.36 \pm 0.07) \log \delta_R^{4+\alpha_\gamma} + (44.61 \pm 0.42)$ with a correlation coefficient $r = 0.616$ and a chance probability of $p < 10^{-4}$, and $\log L_\gamma(\text{erg/s}) = (0.24 \pm 0.05) \log \delta_R^{5+2\alpha_\gamma} + (44.66 \pm 0.42)$ with a correlation coefficient $r = 0.607$ and a chance probability of $p < 10^{-4}$ for the whole sample of 43 sources from Hovatta et al. (2009). The corresponding plots are shown in Fig 2.

$\log L_\gamma(\text{erg/s}) = (0.44 \pm 0.09) \log \delta_R^{4+\alpha_\gamma} + (44.65 \pm 0.37)$ with a correlation coefficient $r = 0.624$ and a chance probability of $p < 10^{-4}$, and $\log L_\gamma(\text{erg/s}) = (0.30 \pm 0.06) \log \delta_R^{5+2\alpha_\gamma} + (44.67 \pm 0.37)$ with a correlation coefficient $r = 0.620$ and a chance probability of $p < 10^{-4}$ for the whole sample of 42 sources from Fan et al. (2009). The corresponding plots are shown in Fig 3.

For each sample, we also investigated the correlation for the subclasses of FSRQs, and BLs, the corresponding results are listed in Table 2. In the Table, column (1) gives the relationship, column (2) sample, T for the whole sample, F for FSRQs, H+L for BLs, column (3) regression constant a , column (4) 1σ uncertainty for constant a , column (5) slope b , column (6) 1σ uncertainty for slope b , column (7) correlation coefficient $r_{L\delta}$, column (8) number of sources, N , column (9) chance probability p , column (10) reference for the used radio Doppler factor, L99: Lähtenmäki & Valtaoja (1999); H09: Hovatta et al. (2009); and F09: Fan et al. (2009).

3. Discussion

Blazars are a special subclass of AGNs showing extreme observational properties, which are believed to be due to the beaming effect. The beaming model was adopted to explain both the particularly observational similarities and some observational differences between BL lacertae

objects and FSRQs. For the two types of BL Lacertae objects (RBLs and XBLs), the beaming effect can explain some of the observational differences between them (see Fan et al. 1997; Fan & Xie 1996; Georganopoulos & Marscher 1999; Xie et al. 1991) although the viewing angle alone can not explain all the difference between RBLs and XBLs (Sambruna et al. 1996, Fossati et al. 1998).

The Fermi mission has detected a lot of blazars (Abdo et al. 2010a, Ackermann et al. 2011a), which shed new lights on the emission mechanisms of blazars, particularly on the highly energetic γ -ray emissions. There are many indirect evidences to show that the γ -ray emissions are strongly beamed (see Arshakian et al., 2010, Fan et al. 2008, Huang, et al., 1999, Kovalev et al., 2009, Pushkarev et al., 2010, and Savolainen et al., 2010).

In the present paper, we chose the Fermi sources with available radio Doppler factors for the discussion of the beaming effect in the γ -ray region, and got a sample of 59 Fermi sources. To show the representation of the sample, we put them in a plot of the γ -ray flux density against the 15GHz radio flux density (Fig. 4), the 15GHz radio flux densities are from a paper by Ackermann et al. (2011b). Out of the 59 sources, 43 have corresponding 15 GHz radio data (namely 31 sources from both Lähtenmäki & Valtaoja 1999 and Fan et al. 2009, and 34 sources from Hovatta et al. 2009 have 15GHz radio data). In the plot, the γ -ray flux density is calculated at 1GeV, the 43 filled points stand for the sources included in Table 1 of this paper while the open circles for the rest sources in the paper by Ackermann et al. (2011b). From the plot, it is clear that the sources considered in the present paper show higher γ -ray and 15 GHz radio flux densities than do the rest sources. When the 8.4GHz radio data are used for a plot, similar result can be obtained, namely the sources considered in the present sample show higher γ -ray and 8 GHz radio flux densities.

In a beaming model, the γ -ray flux density S_ν^{ob} , is expected to be associated with the Doppler factor, δ_ν by $S_\nu^{\text{ob}} \propto \delta_\nu^{3+\alpha_\nu}$ in a synchrotron self-Compton (SSC) model, or $S_\nu^{\text{ob}} \propto \delta_\nu^{4+2\alpha_\nu}$ in an external Compton (EC) model, here, α_ν is the spectral index ($f_\nu \propto \nu^{-\alpha_\nu}$) (see Dermer 1995). These indices are true for transient emission features, whereas in a steady jet, the indices are smaller by one. For the γ -ray luminosity, we can expect that $L_\gamma^{\text{ob}} \propto \delta_\nu^{4+\alpha_\gamma}$ in a synchrotron self-Compton (SSC) model, and $L_\gamma^{\text{ob}} \propto \delta_\nu^{5+2\alpha_\gamma}$ in an external Compton (EC) model. Therefore, for the γ -ray sources, if we have a complete sample with available γ -ray Doppler factor, δ_γ , then we can use the correlation between the γ -ray luminosity and the γ -ray Doppler factor, δ_γ , to check the emission mechanism for the γ -rays. Unfortunately, we do not have δ_γ for the sources. If the γ -ray Doppler factor, δ_γ , is the same as the radio Doppler factors, δ_R , then we can use the radio Doppler factor in our consideration. In the present paper, we compiled the radio Doppler factors from 3 papers (see Lähtenmäki & Valtaoja 1999; Hovatta et al. 2009; Fan et al. 2009) for the γ -ray sources (Abdo et al. 2010a) and got 3 corresponding samples. For each sample, we

Fig. 1. Plot of the γ -ray luminosity, $\log L_\nu$ (ergs/s) against $\log \delta_R^{4+\alpha_\gamma}$ on the left panel and against $\log \delta_R^{5+2\alpha_\gamma}$ on the right panel for the sources whose radio Doppler factors are from Lähteenmäki & Valtaoja (1999). The plus stands for FSRQs, the open square stands for LBLs, and the filled squares for HBLs. The lines are for best fitting results. The solid line stands for the whole sample (F+L+H), the dotted line for FSRQs (F), the broken-line for BLs (H+L).

Fig. 2. Plot of the γ -ray luminosity, $\log L_\nu$ (ergs/s) against $\log \delta_R^{4+\alpha_\gamma}$ on the left panel and against $\log \delta_R^{5+2\alpha_\gamma}$ on the right panel for the sources whose radio Doppler factors are from Hovatta et al. (2009). The symbols and lines have the same meanings as in Fig. 1.

Fig. 3. Plot of the γ -ray luminosity, $\log L_\nu$ (ergs/s) against $\log \delta_R^{4+\alpha_\gamma}$ on the left panel and against $\log \delta_R^{5+2\alpha_\gamma}$ on the right panel for the sources whose radio Doppler factors are from Fan et al. (2009). The symbols and lines have the same meanings as in Fig. 1.

Fig. 4. Plot of the γ -ray flux density, $\log S_{1\text{GeV}}$ (pJy) against the radio flux density $\log S_{15\text{GHz}}$ (mJy). The 15GHz data are from the paper by Ackermann et al.(2011b), the 43 black points stand for the sources included in Table 1 while the open circles for the sources that have 15GHz data but not in our sample.

Table 2. Correlations between the γ -ray luminosity and the Radio Doppler Factor

Relat. (1)	Samp. (2)	a (3)	Δa (4)	b (5)	Δb (6)	$r_{L\delta}$ (7)	N (8)	p (9)	Ref for δ (10)
$\log\delta^{4+\alpha}-\log L_\gamma$	T	44.67	0.42	0.41	0.09	0.597	43	< 0.0001	L99
$\log\delta^{4+\alpha}-\log L_\gamma$	F	45.27	0.59	0.34	0.11	0.510	28	0.00556	L99
$\log\delta^{4+\alpha}-\log L_\gamma$	H+L	44.74	0.61	0.26	0.15	0.428	15	0.11153	L99
$\log\delta^{5+2\alpha}-\log L_\gamma$	T	44.71	0.42	0.28	0.06	0.590	43	< 0.0001	L99
$\log\delta^{5+2\alpha}-\log L_\gamma$	F	45.34	0.59	0.22	0.08	0.495	28	0.00744	L99
$\log\delta^{5+2\alpha}-\log L_\gamma$	H+L	44.78	0.61	0.17	0.11	0.413	15	0.12631	L99
$\log\delta^{4+\alpha}-\log L_\gamma$	T	44.61	0.42	0.36	0.07	0.616	43	< 0.0001	H09
$\log\delta^{4+\alpha}-\log L_\gamma$	F	44.69	0.83	0.36	0.13	0.489	27	0.00963	H09
$\log\delta^{4+\alpha}-\log L_\gamma$	H+L	44.86	0.58	0.26	0.13	0.477	16	0.0615	H09
$\log\delta^{5+2\alpha}-\log L_\gamma$	T	44.66	0.42	0.24	0.05	0.607	43	< 0.0001	H09
$\log\delta^{5+2\alpha}-\log L_\gamma$	F	44.79	0.84	0.24	0.09	0.473	27	0.01271	H09
$\log\delta^{5+2\alpha}-\log L_\gamma$	H+L	44.90	0.59	0.17	0.09	0.461	16	0.07205	H09
$\log\delta^{4+\alpha}-\log L_\gamma$	T	44.65	0.37	0.44	0.09	0.624	42	< 0.0001	F09
$\log\delta^{4+\alpha}-\log L_\gamma$	F	45.17	0.58	0.38	0.13	0.522	26	0.00622	F09
$\log\delta^{4+\alpha}-\log L_\gamma$	H+L	44.59	0.47	0.35	0.13	0.580	16	0.01854	F09
$\log\delta^{5+2\alpha}-\log L_\gamma$	T	44.67	0.37	0.30	0.06	0.620	42	< 0.0001	F09
$\log\delta^{5+2\alpha}-\log L_\gamma$	F	45.20	0.58	0.26	0.09	0.516	26	0.00701	F09
$\log\delta^{5+2\alpha}-\log L_\gamma$	H+L	44.61	0.48	0.24	0.09	0.569	16	0.02155	F09

Note: $\log L_\gamma = (a \pm \Delta a) + (b \pm \Delta b) \log \delta^q$, $q = 4 + \alpha$ (or $5 + 2\alpha$)

made linear regression fitting for the whole sample, and the sub-samples for FSRQs and BL Lacs (LBLs+HBLs) respectively. Significant correlations are obtained for all the relations (see Figs 1, 2, and 3, and Table 2). However, Table 2 shows that all the slopes are much below the expected value, 1.0. The reasons are probably that 1) the present sample is too small; 2) the γ -ray Doppler factors are not the same as the radio Doppler factors; 3) the γ -ray emissions and the radio emissions used for the radio Doppler factors are not simultaneous; or 4) the correlations are from the effect of a common redshift as discussed below.

If the correlation is an apparent one caused by the redshift, which is correlated with the luminosity and the Doppler factor, δ , then it is important for us to remove the effect of a common redshift. To do so, we can use the method (Padovani 1992) to deal with the relevant data. If r_{ij} is the correlation coefficient between x_i and x_j , in the case of three variables the correlation coefficient between two of them, removing the effect of the third one is (see also Fan et al. 1996)

$$r_{12,3} = \frac{r_{12} - r_{13}r_{23}}{\sqrt{(1 - r_{12}^2)(1 - r_{23}^2)}}.$$

We adopted this formulae to the analysis, and listed the results in Table 3, in which, Col. (1) gives the correlations, Col. (2) the sample, Col. (3) correlation coefficient for luminosity and the radio Doppler factor, the values are the same as that in Col. (7) of Table 2, Col. (4) correlation coefficient for redshift and the radio Doppler factor ($\log z - \log \delta^{4+\alpha}$, or $\log z - \log \delta^{5+2\alpha}$), Col. (5) correlation coefficient for redshift and the γ -ray luminosity, $\log L_\gamma - \log z$, Col. (6) correlation coefficient removing the

effect of a common redshift, Col. (7) number of sources, N, Col. (8) chance probability, p , Col. (9) the existence of the correlation, 'No' means that the correlation, after removing the effect of a common redshift, does not exist any more; 'Mar' means there is a marginal correlation after removing the effect of a common redshift; 'Yes' means that there is still a correlation after removing the effect of a common redshift, Col. (10) the reference for the radio Doppler factors.

From Table 3, for the whole sample, we have $r_{L\delta,z} = 0.245$ (L99), 0.211 (H99), and 0.243 (F09) for the case of $\log \delta^{4+\alpha} - \log L_\gamma$, and $r_{L\delta,z} = 0.222$ (L99), 0.187 (H99), and 0.232 (F09) for the case of $\log \delta^{5+2\alpha} - \log L_\gamma$. The chance probability is greater than 10%, suggesting that there is no more correlation.

For FSRQs, we have $r_{L\delta,z} = 0.422$ (L99), 0.480 (H99), and 0.363 (F09) for the case of $\log \delta^{4+\alpha} - \log L_\gamma$, and $r_{L\delta,z} = 0.395$ (L99), 0.451 (H99), and 0.353 (F09) for the case of $\log \delta^{5+2\alpha} - \log L_\gamma$. The chance probability is less than 5% for the L99 and H09 samples, suggesting that the correlation exists for FSRQs. The chance probability are 6.6% and 7.4% for F09 sample, implying a marginal correlation. We can say that there is a correlation between the γ -ray luminosity and the radio Doppler factor ($\delta^{4+\alpha}$ or $\delta^{5+2\alpha}$). This result implies that the γ -ray emissions are really correlated with the Doppler factors, and that the γ -ray Doppler factors are associated with the radio Doppler factor in FSRQs. We also found, for each sample, that there is no much difference between the correlation coefficient $r_{L\delta,z}$ for $\log \delta^{3+\alpha} - \log L_\gamma$ and that for $\log \delta^{4+2\alpha} - \log L_\gamma$. In addition, there is no much difference in the correlation coefficient $r_{L\delta,z}$ for the 3 samples. So,

based on the analysis, it is difficult for us to tell one emission mechanism (SSC or EC) from another for FSRQs. The reasons are perhaps 1) the present samples are small and not complete and 2) the γ -ray Doppler factors are not the same as the radio Doppler factor.

For BLs, however, there is no more correlation between the luminosity and the Doppler factor if the effect of a common redshift is considered. The correlation coefficients are, $r_{L\delta,z} = -0.048$ (L99), -0.105 (H09), and 0.012 (F09) for the case of $\log\delta^{4+\alpha} - \log L_\gamma$, and $r_{L\delta,z} = -0.065$ (L99), -0.127 (H09), and -0.011 (F09) for the case of $\log\delta^{5+2\alpha} - \log L_\gamma$. The apparent correlation between the luminosity and the Doppler factor is from the effect of a common redshift. Does that mean the γ -ray Doppler factors in BLs is quite different from the radio Doppler factor? From above analysis, it suggests that the γ -ray emission mechanism in FSRQs is different from that in BLs or the dependence of luminosity on Doppler factor in FSRQs is different from that in BLs. We also noticed that the BL sub-samples consist of only 15 or 16 objects, the samples are too small. It is hard to draw a conclusion about the emission process differences between FSRQs and BL Lacs based on a sample of BL Lacs that has only 15 or 16 sources. A complete sample with available γ -ray Doppler factor should be obtained for the investigation.

When we considered the correlation between the γ -ray luminosity and the radio Doppler factor, $\log\delta - \log L_\gamma$, we have that there are correlations between them for the whole sample and the sub-samples for each of the 3 samples. The correlation analysis results are shown in Table 4. We can see clearly that there is still a correlation between the γ -ray luminosity and the radio Doppler factor for FSRQs even the effect of a common redshift is removed, however the partial correlation analysis does not show a correlation for the small BL Lac sample.

In the present paper, we compiled 3 samples of Fermi loud blazars with available radio Doppler factors. For each sample, we investigated the correlation between the γ -ray luminosity, $\log L_\gamma$, and the radio Doppler factor ($\log\delta^{4+\alpha}$ or $\log\delta^{5+2\alpha}$) for the whole sample, FSRQs and BLs respectively. Following conclusions can be obtained.

1. There are apparent correlations between the γ -ray luminosity, $\log L_\gamma$, and the radio Doppler factor ($\log\delta^{4+\alpha}$ or $\log\delta^{5+2\alpha}$) for the whole sample, FSRQs and BLs.
2. When redshift effect is excluded, there are still correlations between the γ -ray luminosity, $\log L_\gamma$, and the radio Doppler factor ($\log\delta^{4+\alpha}$ or $\log\delta^{5+2\alpha}$) for FSRQs suggesting that there is a real correlation between the γ -ray luminosity and the Doppler factor. However, the partial correlation analysis does not show a correlation for the small BL Lac sample.
3. The γ -ray emission mechanism in FSRQs is perhaps different from that in BLs. Or there is a different dependence of the γ -ray emission on the radio Doppler factor between FSRQs and BLs.

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Table 3. Correlations removing the effect of a common redshift

Relat. (1)	Samp. (2)	$r_{L\delta}$ (3)	$r_{z\delta}$ (4)	r_{zL} (5)	$r_{L\delta,z}$ (6)	N (7)	p (8)	Corr (9)	Ref for δ (10)
$\log\delta^{4+\alpha}-\log L_\gamma$	T	0.597	0.570	0.879	0.245	43	0.116	No	L99
$\log\delta^{4+\alpha}-\log L_\gamma$	F	0.510	0.333	0.774	0.422	28	0.026	Yes	L99
$\log\delta^{4+\alpha}-\log L_\gamma$	H+L	0.428	0.511	0.877	-0.048	15	0.846	No	L99
$\log\delta^{5+2\alpha}-\log L_\gamma$	T	0.590	0.572	0.879	0.222	43	0.149	No	L99
$\log\delta^{5+2\alpha}-\log L_\gamma$	F	0.495	0.335	0.774	0.395	28	0.039	Yes	L99
$\log\delta^{5+2\alpha}-\log L_\gamma$	H+L	0.413	0.502	0.877	-0.065	15	0.816	No	L99
$\log\delta^{4+\alpha}-\log L_\gamma$	T	0.616	0.614	0.868	0.211	43	0.168	No	H09
$\log\delta^{4+\alpha}-\log L_\gamma$	F	0.489	0.254	0.780	0.480	27	0.013	Yes	H09
$\log\delta^{4+\alpha}-\log L_\gamma$	H+L	0.477	0.586	0.882	-0.105	16	0.689	No	H09
$\log\delta^{5+2\alpha}-\log L_\gamma$	T	0.607	0.616	0.868	0.187	43	0.213	No	H09
$\log\delta^{5+2\alpha}-\log L_\gamma$	F	0.473	0.257	0.780	0.451	27	0.019	Yes	H09
$\log\delta^{5+2\alpha}-\log L_\gamma$	H+L	0.461	0.578	0.882	-0.127	16	0.603	No	H09
$\log\delta^{4+\alpha}-\log L_\gamma$	T	0.624	0.600	0.896	0.243	42	0.120	No	F09
$\log\delta^{4+\alpha}-\log L_\gamma$	F	0.522	0.407	0.835	0.363	26	0.066	Mar.	F09
$\log\delta^{4+\alpha}-\log L_\gamma$	H+L	0.580	0.641	0.899	0.012	16	0.968	No	F09
$\log\delta^{5+2\alpha}-\log L_\gamma$	T	0.620	0.600	0.896	0.232	42	0.136	No	F09
$\log\delta^{5+2\alpha}-\log L_\gamma$	F	0.516	0.405	0.835	0.353	26	0.074	Mar.	F09
$\log\delta^{5+2\alpha}-\log L_\gamma$	H+L	0.569	0.637	0.899	-0.011	16	0.968	No	F09

Table 4. Correlations for $\log\delta-\log L_\gamma$

Relat. (1)	Samp. (2)	a (3)	Δa (4)	b (5)	Δb (6)	$r_{L\delta}$ (7)	N (8)	p (9)	$r_{L\delta,z}$ (10)	p_z (11)	Corr (12)	Ref (13)
$\log\delta-\log L_\gamma$	T	44.60	0.42	2.32	0.47	0.611	43	< 0.0001	0.269	0.081	Mar.	L99
$\log\delta-\log L_\gamma$	F	45.13	0.59	2.03	0.61	0.545	28	0.00271	0.386	0.049	Yes	L99
$\log\delta-\log L_\gamma$	H+L	44.66	0.59	1.50	0.79	0.466	15	0.07999	0.069	0.783	No	L99
$\log\delta-\log L_\gamma$	T	44.50	0.42	2.05	0.39	0.633	43	< 0.0001	0.274	0.072	Mar.	H09
$\log\delta-\log L_\gamma$	F	44.54	0.81	2.11	0.69	0.522	27	0.00523	0.548	0.004	Yes	H09
$\log\delta-\log L_\gamma$	H+L	44.76	0.57	1.48	0.65	0.517	16	0.04033	-0.048	0.847	No	H09
$\log\delta-\log L_\gamma$	T	44.63	0.37	2.44	0.47	0.632	42	< 0.0001	0.301	0.048	Yes	F09
$\log\delta-\log L_\gamma$	F	45.10	0.58	2.15	0.69	0.535	26	0.00482	0.491	0.009	Yes	F09
$\log\delta-\log L_\gamma$	H+L	44.55	0.46	1.91	0.67	0.607	16	0.01262	-0.004	0.988	No	F09

Note: $\log L_\gamma = (a \pm \Delta a) + (b \pm \Delta b) \log \delta$

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